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SUPERCOMPUTING AND COMPUTATIONAL PENETRATION MECHANICS

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K.D. KIMSEY

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U.S. ARMY LABORATORY COMMAND

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13. ABSTRACT *(Maximum 200 words)*

This report provides an overview of various aspects of numerical simulation of the dynamics of impacting continuous bodies. Emphasis is placed on impact scenarios, wherein the loading conditions are sufficiently intense to produce large deformations and penetrations. Such events are characterized by loading and response times in the microsecond regime. Furthermore, the deformations are highly localized and are governed by properties of the materials within the affected region as opposed to the global characteristics of the structure in which they are contained. Selected two- and three-dimensional examples of high velocity penetration are presented. Practical aspects of performing large-scale simulations of penetration phenomena on modern supercomputers are discussed. Keywords:

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1. PENETRATION MECHANICS

Kinetic energy penetration phenomena are of interest in a variety of problem areas. Though often associated with military applications (terminal ballistics), the same considerations apply in problems involving containment of high-mass or high-velocity debris due to accidents or high-rate energy release, the transportation safety of hazardous materials, safety of nuclear reactor containment vessels, the design of lightweight body armors, the erosion and fracture of solids due to repeated impacts by liquid or solid particles, and the protection of spacecraft from meteoroid impact.

A kinetic energy projectile uses the energy of its motion to push its way into (penetrate) and perhaps through (perforate) a barrier. This is opposed to the effects of chemical energy stored in energetic materials, such as explosives. Figure 1 depicts a generic kinetic energy penetration process (Silsby 1987).

Formally, Backman and Goldsmith (1978) define penetration as the entrance of a missile into a target without completing its passage through the body. This results in the embedment of the projectile and formation of a cavity. If the projectile rebounds from the impacted surface or penetrates along a curved trajectory emerging through the impacted surface with a reduced velocity, the process is termed a ricochet. Perforation, in contrast, is the complete piercing of a target by the projectile. These processes occur in sub-millisecond time frames and, at high velocities, result in extensive damage to projectile and target.

Upon impact, compressive stress waves are generated in both projectile and target. They move with either the sound speed of the materials making up the projectile and target for subsonic impacts or at the shock velocity for hypervelocity impacts [refer to Zukas et al. (1982), Johnson (1972), Kolsky (1963), Rinehart (1975), or Macaulay (1987) for descriptions of the behavior of materials and structures under impact loading and stress wave propagation in solids]. These are followed by slower moving shear waves. For sufficiently high-impact velocities, relief waves will be generated in the rod due to the lateral free surfaces, creating a two-dimensional stress state behind the compressive front for normal impacts, or a three-dimensional stress state for oblique impacts, since these involve asymmetric bending waves as well (Figure 2). In the target, the two wave systems will propagate until they interact with a free surface. There, in order to satisfy the free surface boundary conditions, compressive pulses will be reflected as tension; and, if both the amplitude of the tensile stress pulse

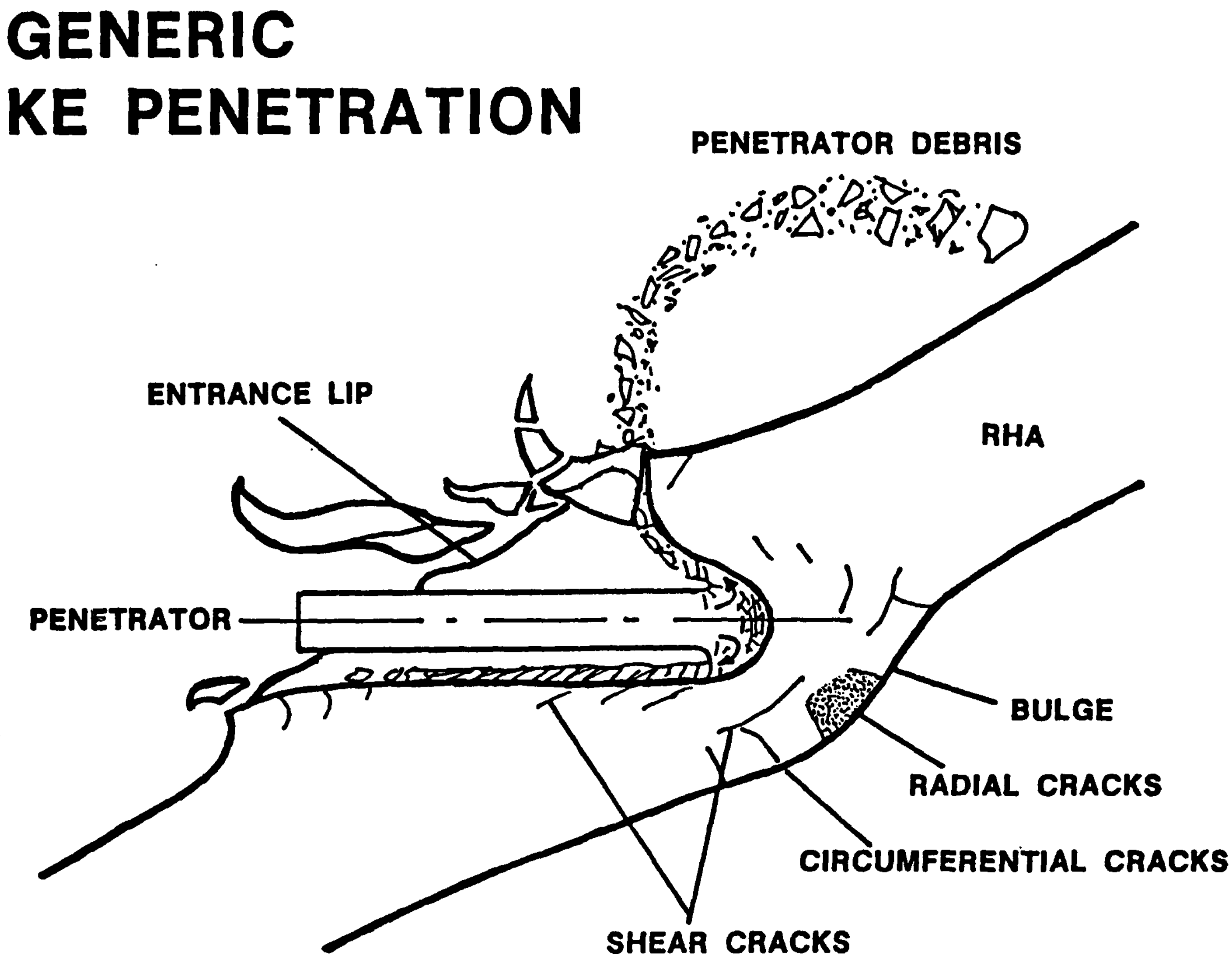

Figure 1. Generic Kinetic Energy Penetration (Silsby 1987).

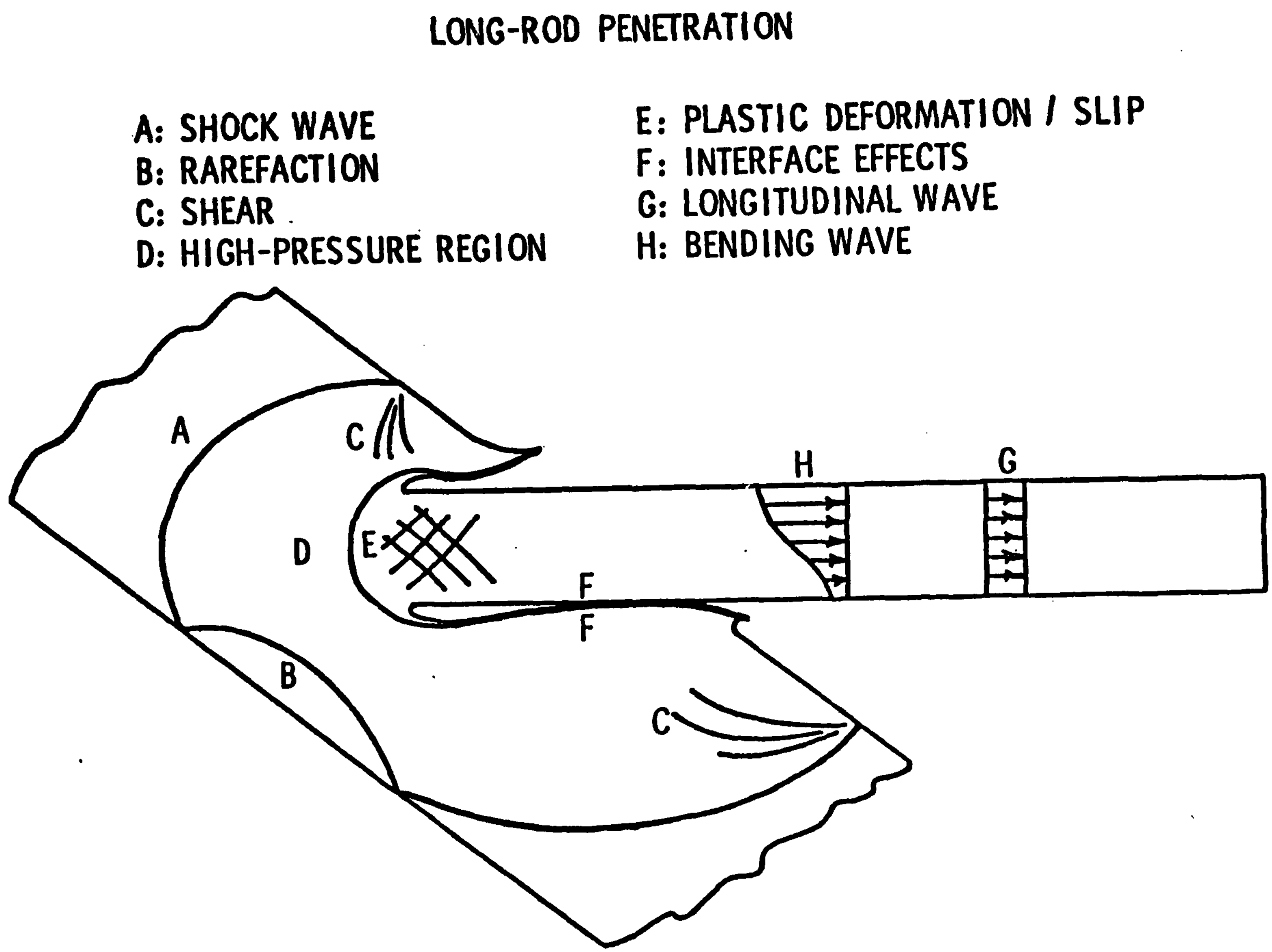

Figure 2. Wave Propagation Effects in Long Rod Penetration (Wright 1981).

and its duration at a point in the material are sufficient, material failure by a variety of the mechanisms can occur. Depending on the material, geometry, and impact conditions (obliquity, pitch, yaw), a number of phenomena can be observed. The target may bulge, crack, spall, petal, or exhibit shear instabilities (Figure 2), while the projectile can be deflected from its original flight path, lose its nose, break, erode, bend, and pick up additional yaw (Figure 3).

Table 1 lists a summary of effects observed in both projectile and target in the penetration/ perforation processes. A complete description of the dynamics of impacting solids would require that account be taken of all of these factors. It is evident that this is an extremely difficult problem which has defied complete solution for over a century. An analytical approach would not only be quite formidable, but would also require a degree of material characterization under high strain-rate loading that could not be attained in practice. Hence, there is heavy reliance in penetration mechanics on experimentation.

A typical instrumented range setup for high-velocity impact studies is shown in Figure 4. The launching of sub-caliber projectiles requires the use of sabots, pusher plates, and obturators. These must be stripped away before the projectile strikes the target so as not to obscure observations of the mechanics of impact. Since the energy transfer on impact results in an intense flash of light which obscures high-speed photographic records, reliance in many facilities is placed on x-ray illumination. Orthogonal pairs of x-ray tubes may be placed at predetermined locations before the target to establish striking velocity and projectile orientation, such as pitch and yaw. Additional pairs of x-ray tubes may be placed behind the target if perforation is expected; and behind target effects, such as residual mass, residual velocity, fragment distribution, etc., need to be studied. High velocity impact test techniques, aside from simple proof tests, vary mainly in the degree of instrumentation provided and, hence, in the amount of data retrieved. Typical ballistic data include:

- The velocity and trajectory of the projectile prior to impact.
- Projectile and target deformation and/or failure as a result of impact.
- Residual masses, residual velocities, and trajectories of fragments generated by the impact process.

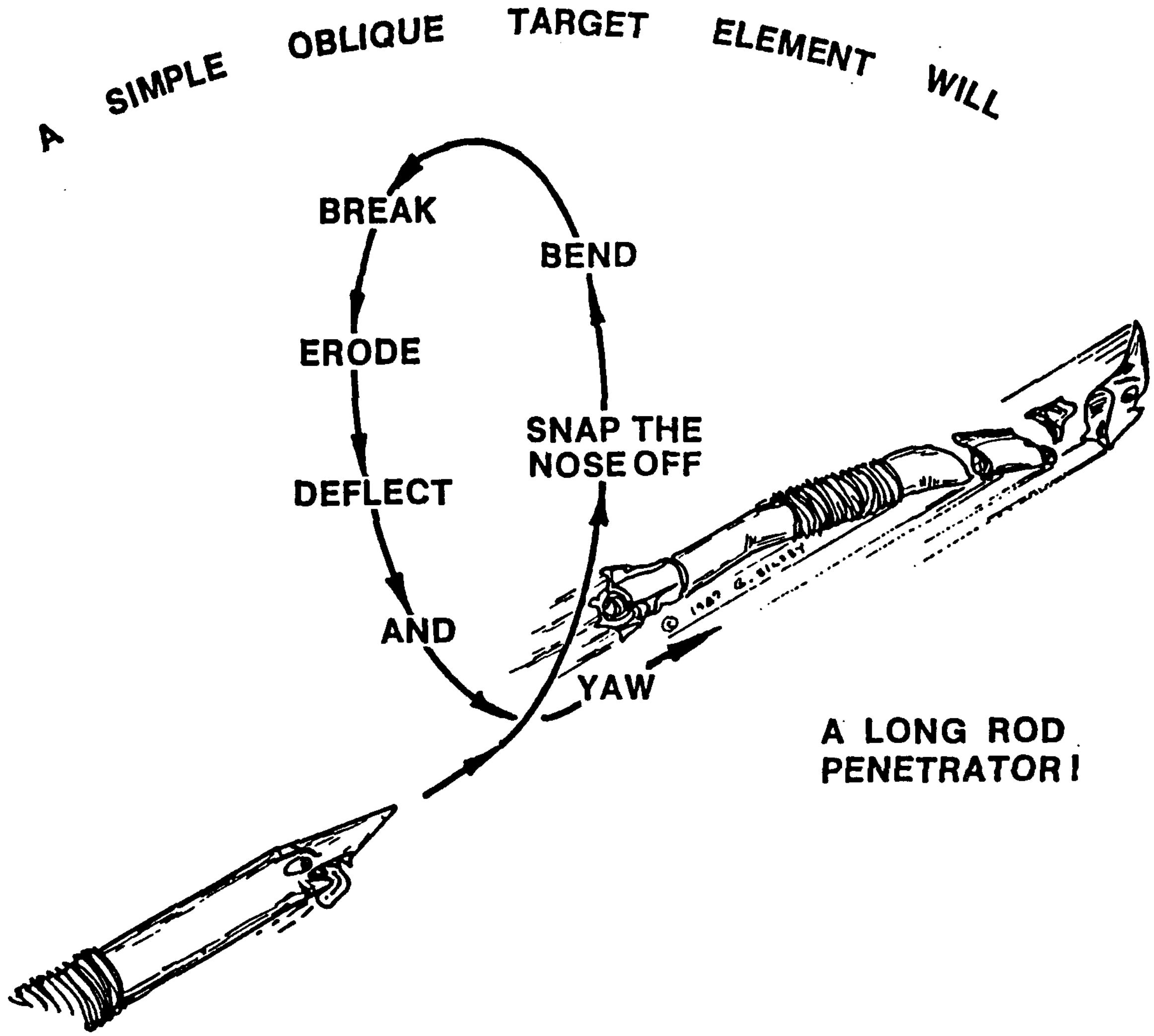

Figure 3. Effects of Obliquity in Kinetic Energy Penetration (Silsby 1987).

Table 1. Projectile and Target Response to Short-Duration Loading (NMAB 1980).

	Pressure (GPa)	Homologous[a] Temperature	Strain	Strain Rate (s^{-1})
Projectile Formation				
Shaped charge jet (3-10 km/sec)	Peak ~ 200 Avg. ~ 20	Peak > 1 Avg. ~ 0.5-0.7	> 10	Peak ~ 10^6-10^7 Avg. ~ 10^4-10^5
Self-forging fragment (1.5-3 km/sec)	Peak ~ 40 Avg. ~ 10	Peak ~ 0.5-0.8 Avg. ~ 0.2	Peak ~ 2 Peak ~ 0.7	Peak ~ 10^6-10^7 Avg. ~ 10^4
Fragmentation (1.3-3 km/sec)	Peak ~ 30 Avg. ~ 2	Ductile ~ 0.3-0.5 Brittle ~ 0.1	Ductile ~ 0.5-1.5 Brittle ~ 0.1-0.2	Peak ~ 10^6-10^7 Avg. ~ 10^4
Target Response				
Gun launched (0.5-1.5 km/sec)	Peak ~ 20-40 Avg. ~ 3-5	Peak ~ 0.2-0.3 Avg. ~ 0.1	Peak > 1 Avg. ~ 0.2-0.3	Peak ~ 10^6-10^7 Avg. ~ 10^4-10^5
Self-forging fragment (1.5-3 km/sec)	Peak ~ 70 Avg. ~ 10	Peak ~ 0.4-0.5 Avg. ~ 0.2	Peak ~ 1 Avg. ~ 0.2-0.3	Peak ~ 10^6 Avg. ~ 10^4-10^5
Shaped charge jet (3-10 km/sec)	Peak ~ 100-200 Avg. ~ 10-20	Peak > 1 Avg. ~ 0.2-0.5	Peak > 1 Avg. ~ 0.1-0.5	Peak ~ 10^6-10^7 Avg. ~ 10^4-10^5

[a] Temperature divided by the melting temperature.

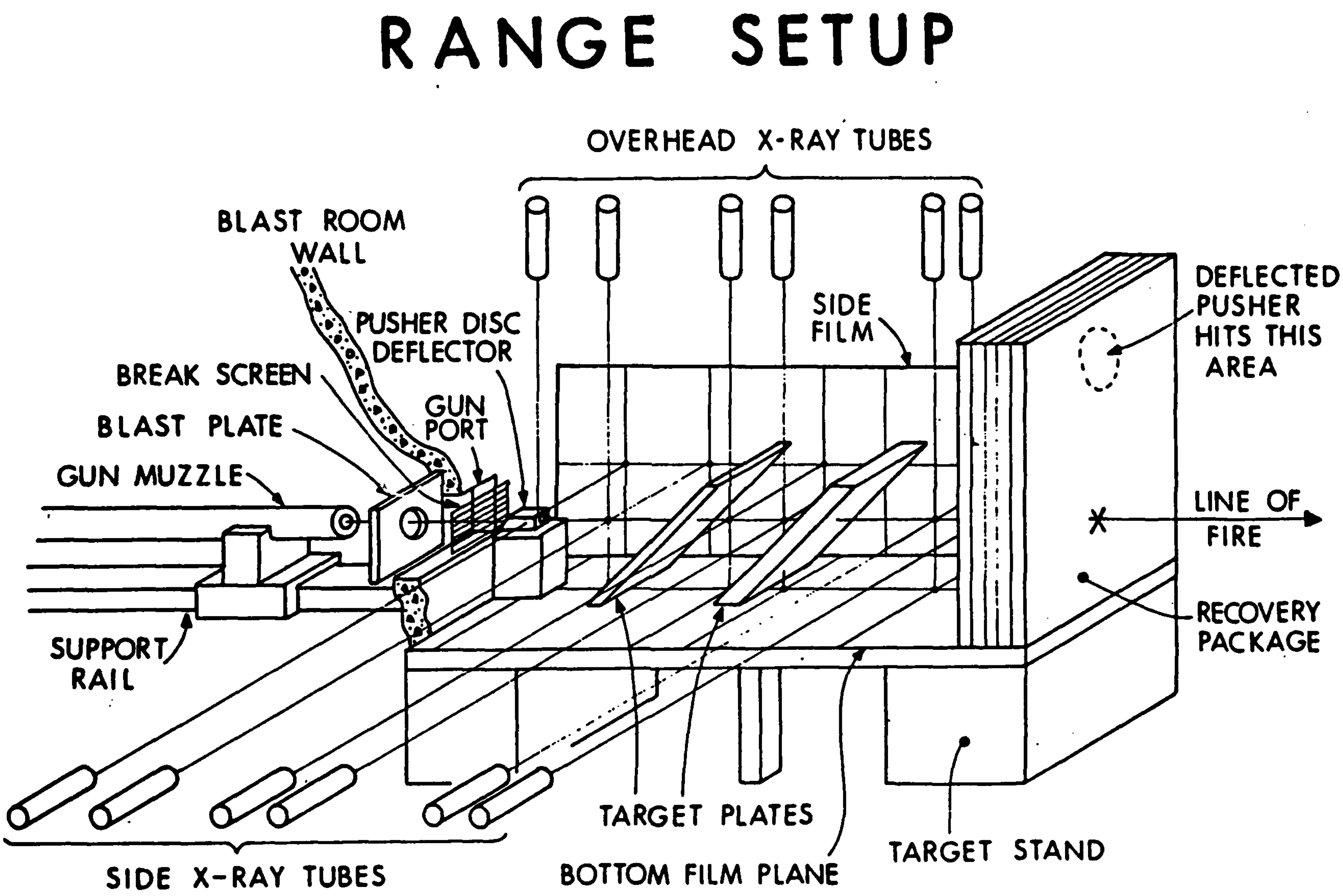

Figure 4. Range Setup.

- The ballistic limit (from a series of tests at different striking velocities). Ballistic limits can be either probabilistic, such as the V50, the velocity at which there is a 50% probability of penetration, or deterministic. For a discussion of ballistic limits, see chapter 5 in Zukas et al. (1982).

2. ANALYTICAL APPROACHES TO PENETRATION PROBLEMS

The fundamental problem of penetration mechanics may be stated roughly as follows (Wright and Frank 1988):

> **"Given a projectile, a target, and details of the initial geometry, kinematics and materials, determine whether or not the target will be perforated upon impact. If perforated, determine what the residual characteristics of the projectile and target will be, and if not, determine how deep a hole will be made."**

Three approaches have traditionally been used, and are still being used, to solve impact problems: empirical formulations (curve fitting), analytical modeling, and numerical studies.

2.1 Empirical Formulations. Empirical relationships rely on an extensive database and, if good correlations are obtained, sometimes prove useful for predicting results of other cases which differ only in minor ways from the given database. Extrapolation beyond that database, however, is extremely dangerous and can lead to substantial errors.

2.2 Analytical Models. Analytical models concentrate on one aspect of the penetration problem (such as plugging, petalling, spall, crater formation, etc.) by introducing simplifying assumptions into the governing equations of continuum physics to reduce these to one- and two-dimensional algebraic or differential equations. Their solution is then attempted. Often, even the simplified set of equations proves intractable, so that additional simplifications are introduced. Frequently, these include empirical factors masquerading as "material constants." Thus, such approaches have the same limitations as empirical equations - they work as long as the database (from which the "material constants" are drawn) is not exceeded. Otherwise, the models must be recalibrated. Many such analyses treat the

projectile as rigid and nondeforming (thus removing quite a bit of mathematical unpleasantness as well as reality from the analytical process) and rely on either momentum or energy balance.

Most existing models consider either a single damage mechanism (plugging, hole enlargement) or conservation law (momentum, energy). A few treat multiple mechanisms, i.e., a combination of such factors as compression, plugging, tearing, target inertia, friction, etc.

In addition to the ever-popular rigidity assumption, several additional hypotheses are frequently used in the development of analytical models:

- Influence is localized. It is assumed that only a small region with dimensions comparable to the projectile diameter is affected by the impact, while the remainder of the target does not influence events.

- Rigid body motions are negligible.

- Thermal phenomena may be neglected. This includes neglect of frictional effects, shock heating and changes in material constitution.

- The impacting bodies are initially stress-free.

As noted by Backman and Goldsmith (1978), these assumptions generally prove useful except in the vicinity of the ballistic limit. The overall aim of many analytical schemes is simplicity. Currently, two-dimensional models have appeared which sacrifice simplicity and generality in favor of a detailed explanation of a single aspect of the impact process. These generally are too complex for closed form solutions and require numerical evaluation. Reviews of analytical modeling of penetration phenomena have been given by Backman and Goldsmith (1978), Zukas et al. (1982), Bodner (1984), Wright and Frank (1988), and Walters and Zukas (1989), as well as sources already mentioned.

An additional drawback is that all but a handful of analytical models, one- or two-dimensional, are derived for problems involving normal incidence. In reality, oblique impacts are the rule, rather than the exception. Moreover, virtually all impact situations are complicated by the projectile's

deviation from its intended flight path. Factors such as the projectile's pitch and yaw can seriously degrade its performance and lead to premature failure.

2.3 Numerical Solutions. For a complete solution of impact problems, one must rely on a numerical solution of the full equations of continuum physics. Finite difference, finite element, and hybrid methods are capable of attacking the entire set of field equations, have greater flexibility and applicability than various approximate models, and can accurately model transient phenomena. They are still approximate in nature (one solves a set of discretized equations rather than the corresponding differential equations); but at present, errors associated with uncertainties in material properties and material failure at high strain rates far exceed the errors inherent in numerical methods.

A number of wave propagation codes (popularly known as "hydrocodes") exist to analyze the response of solids to intense, short-duration loading. They were originally developed to solve problems characterized by:

- The presence of shock waves (alternatively, steep stress or velocity gradients).

- Localized materials response (i.e., situations where the overall geometric configuration of a structure is of secondary importance compared to the constitution and characteristics of the material in the vicinity of the applied load).

- Loading and response times in the sub-millisecond regime.

Excellent results can, and have been, obtained using these so-called "hydrocodes" to solve problems involving many different materials in engineering designs with very complex shapes. Good accuracy has been achieved, in comparison to exact solutions or with experimental results, when the materials involved are very well known and characterized. When this is not done, or when the codes are used as black boxes with engineering materials which are not well understood or characterized, it is not uncommon to obtain qualitatively incorrect solutions.

Wave propagation codes share a number of common features.

2.3.1 Spatial Discretization. The earliest (pre-1975) wave codes made use of finite difference methods to approximate the solution of the governing partial differential equations. Typical of these is the differencing technique used in the TOODY code as described by Walsh (1973). Codes developed in the late 1970s through the 1980s are based on finite element techniques, making use of linear and constant strain triangular and quadrilateral elements in two dimensions, hexahedral or tetrahedral elements in three dimensions. Over the years, experiments have been performed with higher-order elements, such as those found in typical structures codes (e.g., ADINA, MARC, MAGNA, ANSYS). These, however, have not been adopted for general use, since problems modeled with such codes include shock waves (mathematically, discontinuities). There is no gain in accuracy in modeling discontinuities with high-order polynomials, but this causes a considerable increase in computational e'fort. Hence, production codes rely on the simplest spatial discretization techniques.

2.3.2 Time Integration. Solutions are advanced in time through the use of an explicit central difference algorithm. This procedure is straightforward and easily implemented in computer codes.

However, it is only conditionally stable so that the maximum time step, Δt, is controlled by the Courant stability criterion

$$\Delta t = \mathrm{MIN}\{\Delta x / \mathrm{MAX}(c + u)\}$$

where c is the characteristic sound speed of the material, u the particle velocity, Δx the characteristic mesh size, and the minimization is taken over the entire mesh. In short, the smallest cell or element governs the time step for the entire mesh. This has important implications insofar as the cost of a calculation is concerned.

Consider a two-dimensional calculation with a constant cell/element size of Δx in both coordinate directions. The total number of computations performed during a given time step is proportional to the number of cells/elements in the mesh. Assuming N cells in each direction, N*N calculations are performed each cycle to cover the geometric region. Assuming further that M cycles are necessary to reach the desired simulation time (M Δt), the total computational effort for a given simulation is proportional to M*N*N.

If, for the sake of accuracy, the grid is refined using a cell size of 0.5 Δx (i.e., double the resolution), then the time step, which is dependent on the cell size, must also be halved. Hence, the total computational load now becomes 2M*2N*2N = 8M*N*N. In a three-dimensional problem, the load is 16M*N*N*N. If even greater resolution is required, the calculation can become economically prohibitive, or even impossible, if the available central memory of the computer is exceeded. Many of the existing wave propagation codes do not require that the entire computational mesh be stored in central memory simultaneously. A portion of the mesh is kept in core, the remainder being buffered in and out as required. This eliminates restrictions on spatial resolution but introduces other problems. As resolution (mesh size) is increased, more and more of the available central processing unit time is spent buffering information between central memory and mass storage, so that a progressively smaller and smaller percentage is used to advance the solution in time. Again, economics prevail, effectively limiting problem size.

Hence, there is a need to balance physical and economic factors in many computational efforts. If the wave structure and its related variables (pressure, stress, strain) are required, then the resolution must be sufficient to permit the shortest wavelength of interest to be defined by at least three cells/elements. Resolution of high frequency components is necessary if material failure due to shock wave interactions with material interfaces, geometric boundaries, or each other must be carefully modeled, especially if the failure criterion requires a definition of the pulse shape or an accurate value of peak pressure. Each shock wave will be spread over 3-5 cells/elements and must be tracked from inception to peak value (NMAB 1980).

If, on the other hand, only bulk properties are required (center of mass velocity, the overall shape of the colliding objects), then grid requirements can be relaxed considerably. In some cases, these quantities may be obtained to a first approximation without explicitly accounting for material failure in the calculation.

2.3.3 Artificial Viscosity. Shock waves exist as mathematical discontinuities and cannot be directly accommodated in the continuum formulation, which is the basis of present-day wave propagation codes. To get around this problem, an artificial viscosity is introduced to smear shock fronts over several mesh widths in a calculation. Linear and quadratic terms are commonly available. The former serves principally to spread the wave front over several cells in the direction of propagation and to lower the peak amplitude. The latter is used principally to suppress spurious oscillations

behind the wave front. Very good discussions of the artificial viscosity concept are given by Noh (1976) and Wilkins (1980).

With quadrilateral or hexahedral elements which are underintegrated, an instability can occur, called hourglassing, which is not resisted by internal forces. Artificial viscosity formulations for grid stabilization differ. See the papers by Wilkins (1980), Belytschko, Ong and Liu (1984), Flanagan and Belytschko (1981), Malkus and Hughes (1978), Maenchen and Sack (1964), and Schultz (1985) for representative examples.

2.3.4 Material Models. Metals, until recently, were the materials of primary interest. Hence, the material model in most codes decouples the effects of volumetric and shear behavior. The hydrodynamic component of stress is taken from an equation of state. For impacts where the striking velocity is below the sonic velocity, some variant of the Mie-Gruneisen equation of state is commonly used. Beyond this range (hypervelocity impact), the Tillotson equation of state is favored [see chapters 11 and 12 of Walters and Zukas (1989) for details]. The constitutive model of elastic-plastic behavior is typically in incremental form, employing a von Mises yield criterion and providing for some form of hardening, thermal softening, and strain rate effects. By and large, the essential physics in these codes can be written down on the back of a business envelope. Encoded in FORTRAN, it is usually contained in two or three subroutines. The remainder of the coding - between 10,000 and 125,000 FORTRAN statements - is devoted to assorted bookkeeping: input/output operations, sliding interface logic, material transport, and the like. Because of interest in porous materials, various geological materials, and concrete, many of the newer codes incorporate material models for crushable materials [see chapter 11 in Walters and Zukas (1989)].

2.3.5 Limitations. For computations in the ordnance velocity regime, the principal obstacle is a poor description of the mechanisms of failure under impact loading. Micromechanically based failure models applicable in the high pressure regime for multiaxial, transient loading situations are generally not available. Those that exist (Curran 1982) require an inordinate degree of material characterization. Hence, failure models for codes tend to treat failure as an instantaneous process and require only a single parameter, which can generally be inferred from existing data. On theoretical grounds, this is not a satisfactory state of affairs; but in many cases it produces results which are in agreement with experimental observations and minimizes material characterization costs. Modeling of failure under high-rate loading has been discussed by Zukas (1987).

3. CONSIDERATIONS IN LARGE-SCALE SIMULATIONS OF PENETRATION

A number of points need to be considered before undertaking large-scale computations. The selection of a computational mesh involves trade-offs between accuracy and economics. This was pointed out very clearly in an article by Herrmann (1977). Table 2 lists computer resource requirements for a hypothetical problem for the HULL code (Matuska and Osborn 1986), a major production tool for two- and three-dimensional penetration studies. Since a discrete mesh cannot reproduce the entire frequency spectrum encountered in practice, some a priori decision as to minimum cell/element size must be made by the analyst, which will reproduce, within the desired accuracy, the phenomena of interest. Assume that in two dimensions, a grid of 100 x 100 is adequate for this purpose. The minimum time of interest in stress-wave problems generally involves at least two wave transits across the characteristic length dimension of the problem. Thus, for the minimum resolution of 100 meshes in each coordinate direction, 1,000 time steps is a reasonable requirement to advance the solution to the point where useful information for analysis or design can be extracted. In many practical problems, the motion may need to be followed for tens or hundreds of transit times, with a corresponding increase in the number of time steps.

Table 2 indicates that a two-dimensional calculation with 10,000 cells (or elements) can be performed readily, placing only modest demands on the capabilities of today's supercomputers. Indeed, many such problems could easily be run on older mainframes in reasonable times (2-4 hours). Two-dimensional codes have also been implemented on a host of minicomputers and even on personal computers. On such machines, calculations with 10,000 cells (or elements) have been routinely carried out with run times ranging between 5-20 hours and at a very modest cost.

Three-dimensional problems are the rule rather than the exception in ballistics. These provide the main challenge to computational methods. Extending our hypothetical problem to three dimensions and maintaining even resolution of 100 x 100 x 100 in the three coordinate directions results in a calculation involving 1 million cells (or elements). For penetration problems, this is a very coarse mesh, inadequate to resolve the fine details of pressure, stress, strain, and temperature distribution in the colliding bodies. Equal resolution in all three coordinate directions is generally not possible for practical problems. Some gradation of the mesh is required. If this is not done with great care, spurious signals and assorted numerical artifacts can arise in the calculation leading to instabilities or masking results. Even such a coarse calculation (Table 2) would require between 40-70 hours on a

Table 2. Computer Resource Requirements.

Two-Dimensional Calculations	
Total Number of Cells/Elements	100 x 100
Total Number of Cycles	1,000
Number of Mesh Point Calculations	10M
Cray-2 CPU Time	0.7 hours
Cray X-MP CPU Time	0.4 hours
Memory Requirements	190K words
Three-Dimensional Calculations	
Total Number of Cells/Elements	100 x 100 x 100
Total Number of Cycles	1,000
Number of Mesh Point Calculations	1 billion
Cray-2 CPU Time	67 hours
Cray X-MP CPU Time	39 hours
Memory Requirements	27 million words

current supercomputer. If sufficient memory is not available to run the problem in-core, then extensive buffering between main memory and mass storage is required, further increasing turn-around time and cost (if I/O is a billable item). For sufficiently large problems or a small central memory machine, it is possible to approach situations where the bulk of central processing unit (CPU) time is spent on input-output operations, and only a small fraction is spent in advancing the solution, rendering the computation uneconomical.

This does not necessarily imply that three-dimensional calculations cannot be done. Quite a few practical problems have been addressed with three-dimensional codes [chapter 10 in Zukas et al. (1982)]. However, compromises are required, and these, in turn, require a keen understanding of the physical problem and the effects that various numerical artifacts (e.g., uneven resolution in three coordinate directions, mixing of explicit and implicit integration schemes or explicit-explicit partitions, choice of mesh or element type, use of artificial and hourglass viscosity) have on the solution. Anyone can perform finely resolved one- and two-dimensional calculations almost by rote. A keen knowledge of the problem and numerical simulation methods is required, though, for successful three-dimensional simulations which, with all the compromises, will still be expensive and will require significant computer resources (i.e., memory and secondary storage).

4. EXAMPLES

To illustrate some of the above points, a number of calculations are presented involving the impact of kinetic energy projectiles into both (effectively) semi-infinite and finite thickness targets. The projectiles are made from a high-density material. Targets were rolled homogeneous armor steel. The deviatoric (shear) behavior was modeled using an incremental elastic-plastic formulation following the description given by Wilkins (1964). Material properties were taken from split-Hopkinson bar data reported by Nicholas (1981). The volumetric (high pressure) response was modeled with the Mie-Gruneisen equation of state. Data for the materials used in the calculation were obtained from Kohn (1969).

All calculations were performed with the HULL code (Matuska and Osborn 1986a-c), an Eulerian finite difference code for problems involving wave propagation, high velocity impact, and explosive loading. The calculations were run on a Cray X-MP/48.

4.1 <u>High-Velocity Impact of Segmented Rods</u>. The potential benefits of segmented, long rod penetrators have been known for some time and are based on the qualitative advantage of multiple impacts of well-aligned and well-separated penetrator segments when compared to that of a single equivalent penetrator. Eichelberger (1956) first suggested that the penetration performance of a metallic jet with perfectly aligned, spaced segments could be enhanced by as much as 40% over that of continuous jets. Numerical studies by de Rosset (1981), Kucher (1982), de Rosset and Kimsey (1986), Sedgwick, Waddell and Wilkinson (1987), Scheffler (1989), and Zukas (1989), as well as experiments by Chou (1975), Chou and Toland (1977), Charters (1986a,b), and Bell (1987), among others, have all confirmed the possibility of enhanced penetration with segmented rods. The degree of improvement depends on the striking velocity, the number of segments, the spacing of the segments, impact yaw, and impact obliquity.

The theoretical advantages of segmented rods are often difficult to achieve in practice, owing to problems associated with the launching of segmented projectiles and with maintaining segment separation during flight to the target. A number of candidate configurations were evaluated recently in a combined experimental-numerical program (Sorensen et al., to be published). Some of the test configurations are shown in Figure 5. Segmented tungsten alloy penetrators were confined in an aluminum carrier. The specific geometries modeled with HULL code calculations included:

- Baseline L/D (length-to-diameter) = 15 tungsten alloy monolithic penetrator positioned flush with the impact face of the carrier tube.

- Fifteen segments, each with L/D = 1, spaced one projectile diameter without any filler material between the individual segments.

- Fifteen segments, each with L/D = 1, spaced one projectile diameter with epoxy-fiberglass filler between the individual segments.

- Six segments, each with L/D = 1, spaced four projectile diameters without any filler between the individual segments.

The predicted and measured penetration data, Table 3, show good agreement and demonstrate the utility of large-scale computer simulations for predicting the performance of segmented projectiles at high-velocity impact, provided that material properties obtained from dynamic (wave propagation) experiments are available. Figure 6 shows intrusion of the aluminum carrier between the segments, thus degrading penetration. The presence of the filler eliminates this intrusion and, because in this velocity regime (3 km/sec) density is a dominant factor in the material response, contributes to enhanced penetration by about 14%. Numerical simulations are, thus, effective in identifying the mechanisms which lead to enhanced (or degraded) penetration performance. Since two-dimensional simulations are relatively inexpensive on supercomputers, numerical simulations are also effective in optimizing penetrator design.

4.2 Impacts at Obliquity. Consider next calculations involving the impact of an L/D (length-to-diameter) 19 high-density kinetic energy projectile striking a 5.85-cm-thick target of rolled homogeneous armor at an obliquity of 60° with an initial velocity of 1.5 km/sec. Two calculations were performed for this configuration, one of them two-dimensional, using the plane strain option of HULL, the other a fully three-dimensional calculation.

Two-dimensional plane strain calculations are straightforward enough, relatively inexpensive, and provide some interesting information. At sufficiently early times, they can even be quantitatively correct. However, important physical phenomena are neglected in plane strain simulations, not the

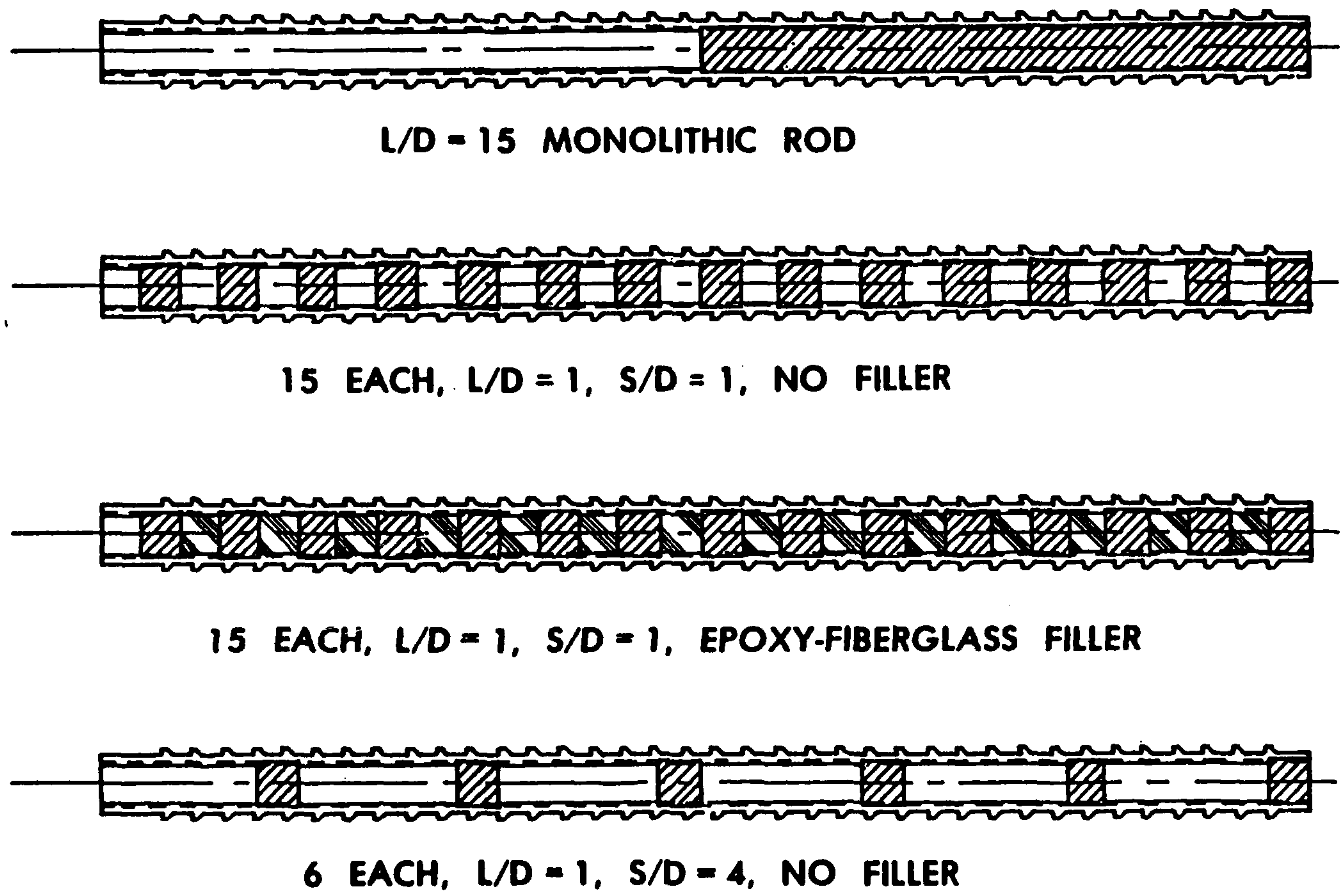

Figure 5. Segmented Penetration Configurations (Sorensen et al., to be published).

Table 3. 125-g Segmented Penetrators vs Semi-Infinite RHA, Striking Velocity 3.0 km/sec.

Shot No.	Penetrator Description # S/D Filler	Measured Penetration, mm	Calculated Penetration, mm	Difference, %
6332	15 1 No	237	228	3.8
6347	6 4 No		138	
6337	15 1 Yes	272	265	2.5
6333	1 - No	212	216	1.8

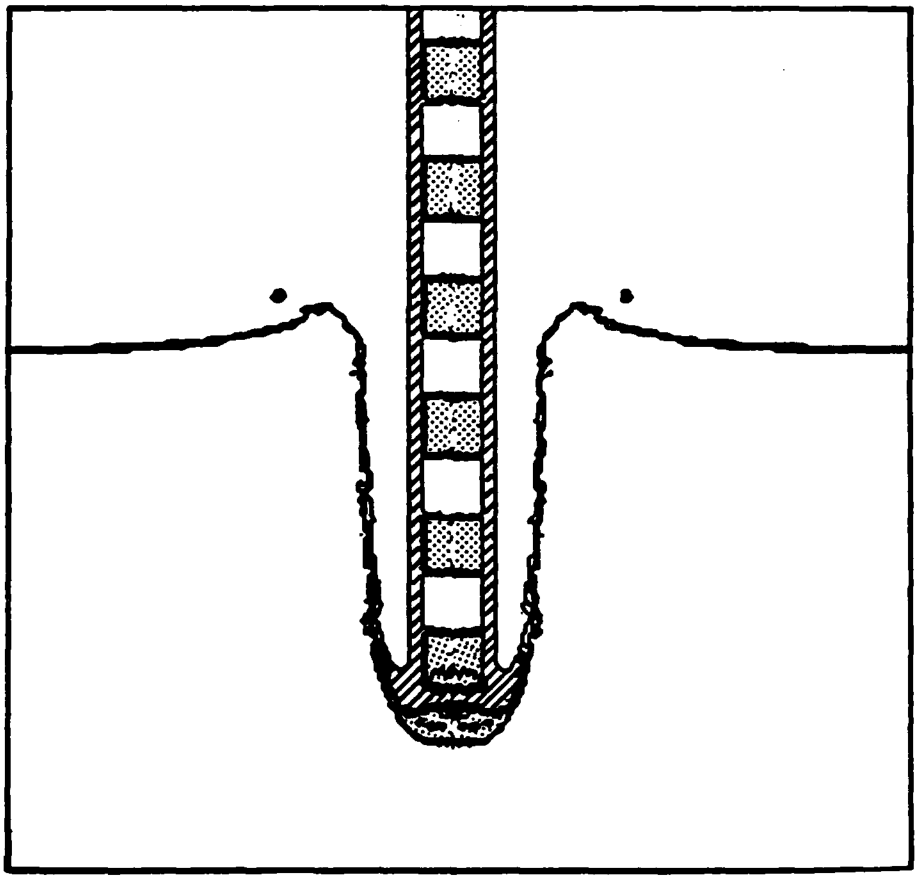

Figure 6. Segmented Rod Penetration at 38 µsec Showing Intrusion of AL Carrier Tube Between Leading Segments (Sorensen et al., to be published).

least of which are the out-of-plane motions leading to lateral stress relaxation. Useful qualitative information about the early stages of an oblique impact can be obtained from plane strain solutions. Their utility degrades with increasing time after impact, however, so that for late times, when important aspects of projectile and target response are being determined, plane strain solutions can be speculative at best. For additional information on plane strain approximations in penetration calculations, see chapter 10 in Zukas et al. (1982) and the references cited therein.

Results of the two-dimensional plane strain calculation are shown in Figure 7. The projectile nose shows considerable deformation. The hole size in the perforated plate is about 5 rod diameters. The calculation was performed with a resolution of 90 x 139 cells in the x- and y-coordinate directions, respectively, and required 15 CPU minutes (alternatively, a "whiz factor" of 1.2×10^{-4} CPU seconds/cell/cycle).

The comparable three-dimensional calculation is shown in Figure 8. With a resolution of 90 x 37 x 139 cells in the three coordinate directions, the calculation required 11.5 hours of CPU time (whiz factor of 1.58×10^{-4} CPU sec/cell/cycle). Note that the hole size in the plate is considerably smaller - just under two rod diameters, which is much closer to reality. Less deformation in the rod nose is indicated as well. On the whole, plane strain results tend to overpredict deformations. Some qualitative information regarding bulk parameters (overall deformations, center-of-mass velocities) can be extracted; but because of the differences between two-dimensional plane strain and three-dimensional simulations, plane strain calculations cannot be relied upon for engineering design studies. Their primary utility is for scoping studies prior to three-dimensional calculations.

5. PRACTICAL CONSIDERATIONS OF LARGE-SCALE SIMULATION

A number of practical problems are encountered in using supercomputers for penetration calculations. Some of these are related to the nature of existing codes and supercomputer architecture.

5.1 Code Considerations. Existing wave propagation codes were developed in the 1960s and early 1970s. They have undergone evolutionary changes since then, attempting to keep pace with theoretical developments and improvements in computer hardware. The latter is not an easy task since typical wave codes range from 20,000-150,000 FORTRAN statements. Updating or rewriting

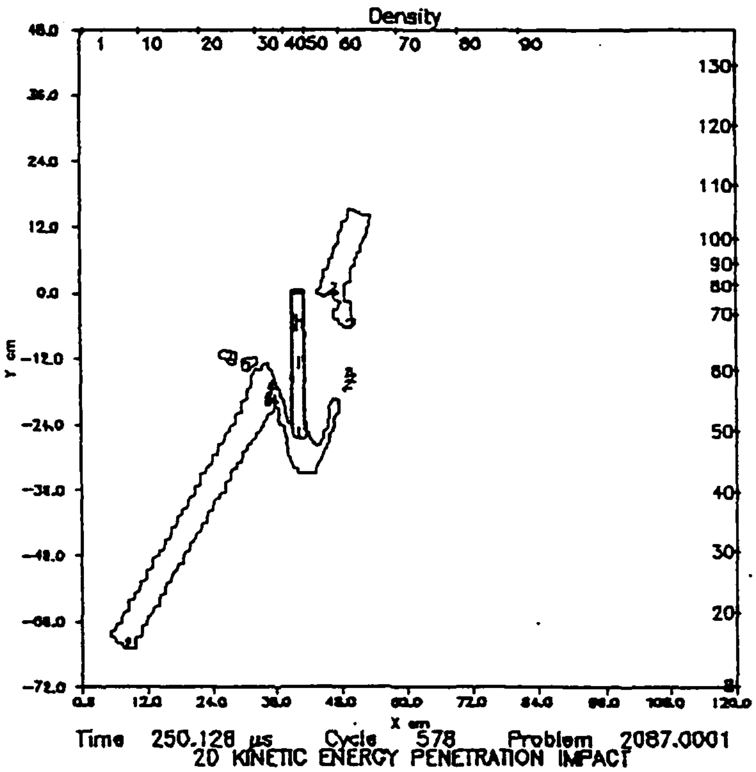

Figure 7. Plane-Strain Solution for an Oblique Impact of a Kinetic Energy Projectile at 250 μsec.

such codes is a nontrivial task. The net result is that many of these codes are not yet fully vectorized. In particular, the sliding interface logic required in Lagrangian codes is particularly difficult to vectorize. Thus, codes imported to supercomputers from other mainframes will not achieve the maximum theoretical gains possible until extensive work is done to optimize them in conjunction with development of improved vector compilers.

The current trend in Eulerian codes is toward higher-order difference schemes for the mass transport algorithms in order to minimize diffusion and allow larger time steps and fewer grid points. However, many practical problems contain regions with very small cross-sections (e.g., projectile sheaths, sharp geometric discontinuities, shaped charge and explosively formed fragment simulations) which must be resolved with at least 3-5 cells (or elements) across the minimum dimension, since wave codes lack the plate and shell elements available in structural dynamics codes. For such situations, higher-order schemes offer improved resolution while incurring a sizable computational penalty. Thus, decreased computational speed must be weighed against gain in accuracy. This would

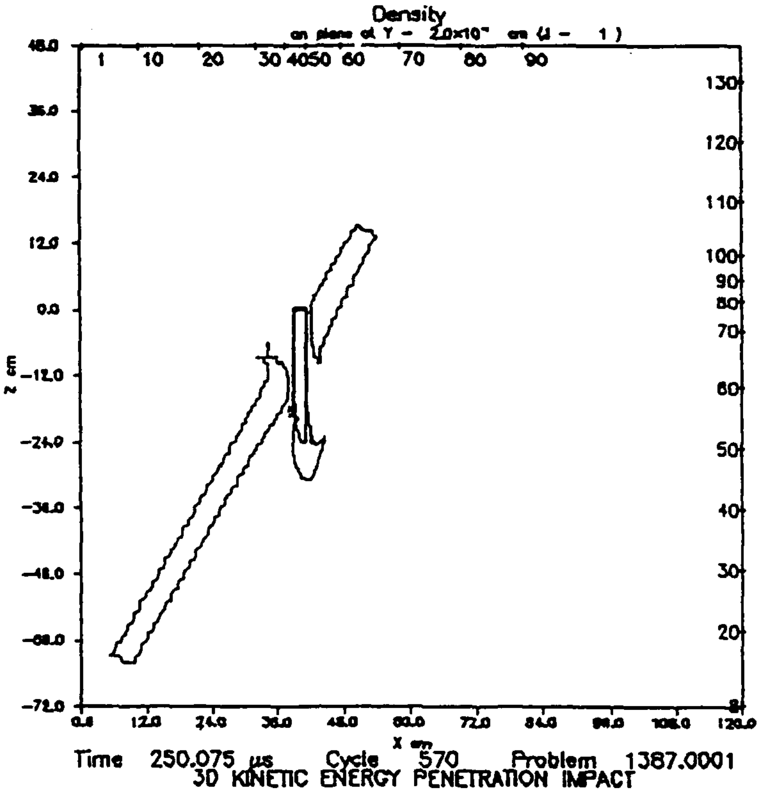

Figure 8. Three-Dimensional Solution for an Oblique Impact of a Kinetic Energy Projectile at 250 μsec.

apply also to situations where shock waves arise spontaneously and need to be tracked in order to correctly compute stress and pressure profiles for advanced models of material failure. The greatest utility of higher-order Eulerian advection schemes would be in reduction of the total number of zones for problems where near-uniform grid size can be maintained throughout the computational grid. This, in practice, is a rarity.

5.2 Hardware/Software Considerations. Supercomputers have the potential to render three-dimensional calculations of penetration feasible on a production basis. However, there are certain features which supercomputer hardware/software must have in order to fully exploit the potential of three-dimensional hydrocodes. These include the following six features.

5.2.1 Adequate Disk Space. Penetration calculations with current software are performed writing restart dumps at predetermined intervals. This information is used to produce graphical results of the penetration process at intermediate times. It is not uncommon to need 10-20 restart dumps to study

the evolution of the penetration process. For three-dimensional calculations, each dump requires 30-70 million words (240-460 megabytes) of storage. A typical capacity of today's disk drives for secondary storage is 1.2-20 gigabytes. Thus, a single three-dimensional Eulerian calculation can seriously strain disk resources. Since supercomputers can only be justified on economic grounds if there are a multiplicity of users, the allocation and impact of disk resources becomes critical. In turn, this implies another requirement, namely file migration and archiving capabilities.

5.2.2 File Migration and Archiving Capabilities. An automatic file migration capability for large-scale simulations is an absolute necessity. It can take up to several wall-clock hours to offload a single restart dump to tape. Without an automatic file migration and archiving capability, valuable time is lost while users manually move restart dumps to tape before restarting the calculation. A robust file migration and archiving capability can circumvent the loss of CPU time due to insufficient disk space. Furthermore, after an initial analysis of data, other information may be needed, or alternative ways of viewing data may be required which necessitates reloading information on tape to disk. A lack of an archiving capability, or the existence of an inefficient one, can result in situations where the bulk of an analyst's time is spent moving data from one device to another, and very little in analyzing results and planning additional calculations. Since engineering man-hours are a major cost component in many projects, inefficient file migration software can contribute very significiantly to the cost of engineering analysis.

5.2.3 System Software Reliability. Operating system, utility and applications software are frequently obtained from multiple vendors. All must interface to work as an harmonious whole. This requires extensive software maintenance. Frequent upgrades to the operating system or system software exacerbate these problems and can render user codes inoperative until the problems are resolved, which can take hours to weeks. Such problems decrease with increasing maturity of the system software. However, some loss of man-hours should be expected at new sites while software capatibility problems are resolved.

5.2.4 Load Balancing. Operating system parameters are tunable to some extent and need to be adjusted for each installation. Ideally, this should be done for the resource requirements of the physical problems, which will be the mainstay of the supercomputer's workload. Frequently, parameters, such as swapping criteria, size of files permitted for execution and storage, the number of jobs permitted in a queue, as well as, definition of the queue classes (i.e., CPU time limit, memory

requiement, file size constraints), and parameters of the job scheduler are set initially by system administrators. These parameters must then be adjusted or "tuned" to values for efficient operation based on the average workload. It may take months before a system is properly "tuned" to yield the desired throughput for interactive, as well as, large-scale batch simulations.

5.2.5 Hardware Reliability. All computer systems (from personal computers through supercomputers) will experience hardware failures. The quantity of hardware (e.g., memory banks, disk drives, tape drives, etc.) on supercomputers is much greater than that on lesser computer systems. Thus, the projected mean time between failure is lower. Additionally, supercomputers press hardware technology to the limit for the sake of speed. If the hardware analysis team is well-staffed, the duration of down time attributed to hardware failures is generally short. However, sudden hardware failures or "crashes" can cause executing jobs to abort or fail to successfully checkpoint. These "crashes" can result in lost CPU as well as man-hours, especially if the hardware problem is intermittent, a situation inherently difficult to trace.

5.2.6 Software Reliability. Any programmer knows the frustration of experiencing software failures. Most often, these software faults reside in the user's software. Less frequently, they also appear in system software. Because of the nature of supercomputing, software problems cannot be routinely located or isolated. Some software problems may not occur until several CPU hours have elapsed. The problem may be intermittent. Tracing these problems, or "debugging," is inherently a slow process, and efforts of this scale may take from a few hours to weeks (on rare occasions, months). If the problem can be duplicated in an isolated section of code, uncertainties may still exist as to the source of the error (e.g., user or system software), if the exact status of program data is not known at program failure. This is a situation where a symbolic debugger is a valuable tool for source-level debugging during program execution. The copious quantities of data accompanying a three-dimensional simulation of a penetration problem add to the already difficult task of software debugging. Finally, system software faults are difficult to debug. In general, code users do not have access to, nor understanding of, system source code, and must rely on phenomenological demonstration of known errant behavior to to identify and isolate errant system source codes. System programmers do not have an understanding of the phenomenology being modeled and operation of user software. Understandably, they are reluctant to accept assertions that errors exist in the system software, unless confronted by overwhelming phenomenological proof or multiple complaints.

6. CONCLUSIONS

Analytical approaches to penetration problems can be grouped into three categories: empirical formulations (curve fitting), analytical modeling, and numerical simulations. While the empirical and analytical approaches can provide an appreciation of the dominant physical processes, they are limited in scope. Curve fits to data do not permit extrapolation beyond the database. Analytical models are based on the perceived dominant mechanism in a penetration process, consider a simple geometry, and almost inevitably assume normal incidence as the price for mathematical tractability. For a complete description of impact problems, recourse must be made to numerical solution of the governing partial differential equations of continuum physics.

Numerical techniques have matured to the point where significant problems of engineering interest involving normal and oblique impacts can be addressed. Excellent results have been obtained, in comparison to exact solutions and experimental results, provided that the material behavior is appropriately modeled, the data for the constitutive model is obtained from a wave propagation experiment at strain rates similar to those encountered in the physical process being studied, and that adequate numerical resolution is used in the computational model. Failure to adhere to these requirements can result in numerical solutions which are not even qualitatively correct.

The advent of supercomputers such as the Cray X-MP and Cray-2 have made three-dimensional simulations of impact problems tractable. However, the demand for computer resources (CPU, memory and disk storage) exceeds availability. This is especially true for modeling complex penetrator/target interactions to study critical defeat mechanisms for armor/anti-armor design studies. While two-dimensional impact problems can require 1-5 CPU hours and less than 0.5 million words of memory, it is not uncommon for three-dimensional simulations to exceed 50 CPU hours and require between 10-100 million words of memory.

The solution of high-velocity impact problems on current supercomputers requires coming to grips with many practical hardware and software considerations which temper the enthusiasm for supercomputing and sorely try the patience of analysts. In no particular order, these include: inadequate disk space, file migration and archiving capabilities, tuning of operating system parameters to suit the local workload, and hardware/software failures. Any one or a combination of these items can have a severe impact for production calculations.

Computational penetration mechanics on supercomputers, then, is an intimate relationship between the physics of the problem and the mechanics of its implementation on a complex computer system. One does not exist without the other. With time and experience, the combination can be optimized to make large-scale simulations an integral part, together with ballistic testing and dynamic material characterization, of the design process of armor/anti-armor systems.

7. REFERENCES

Backman, M. E., and W. Goldsmith. "The Mechanics of Penetration of Projectiles Into Targets," Journal of Engineering Science. Vol. 16, pp. 1-99, 1978.

Bell, L. P. "Evaluation of Segmented and Solid Projectiles During Hypervelocity Flight and Impact." AEDC-TRS-87-V6, Arnold Engineering Development Center, Arnold AFB, TN, March, 1987.

Belytschko, T., J. Ong, and W. K. Liu. "Hourglass Control in Linear and Nonlinear Problems," Computational Methods in Applied Mechanical Engineering. Vol. 43, pp. 251-276, 1984.

Bodner, S. R. "Modelling Ballistic Perforation," Structural Impact and Crashworthiness. Vol. 1, London: Elsevier Applied Science Publishers, 1984.

Charters, A. C. "The Penetration of Rolled Homogeneous Armor by Continuous and Segmented Rods at High Velocity: Theory and Experiments." CR-86-1031, General Research Corporation, Santa Barbara, CA, April 1986 (a).

Charters, A. C. "The Penetration of Rolled Homogeneos Armor by Continuous and Segmented Rods at High Velocity: Theory and Experiments." CR-87-1008, General Research Corporation, Santa Barbara, CA, December 1986 (b).

Chou, P. C., M. Minnich, and L. Gause. "Experimental Study of Multiple Interior Impacts." BRL-CR-199, U.S. Army Balltistic Research Laboratory, Aberdeen Proving Ground, MD, 1975.

Chou, P. C., and R. H. Toland. "Experimental Study of Multiple Interior Impacts," Experimental Mechanics. Vol. 17, No. 6, pp. 201-206, 1977.

Curran, D. R. "Dynamic Fracture," Impact Dynamics. New York: Wiley-Interscience, 1982.

de Rosset, W. S. "Multiple Impacts on Monolithic Steel." Proceedings of the Sixth International Symposium on Ballistics, Orlando, FL, 27-29 October 1981.

de Rosset, W. S., and K. D. Kimsey. "Calculation of Multiple Copper Rod Impacts on Steel Targets." Proceedings of the Ninth International Symposium on Ballistics, Shrivenham, UK, 29 April - 1 May 1986.

Eichelberger, R. J. "Experimental Test of the Theory of Penetration by Metallic Jets," Journal of Applied Physics. Vol. 27, No. 1, pp. 63-68, 1956.

Flanagan, D. P., and T. Belytschko. "A Uniform Strain Hexahedron and Quadrilateral with Orthogonal Hourglass Control," International Journal of Numerical Methods in Engineering. Vol. 17, pp. 679-706, 1981.

Herrmann, W. "Current Problems in the Finite Difference Solution of Stress Waves," Nonlinear Waves in Solids. Proceedings of the Workshop at the University of Illinois at Chicago Circle, pp. 73, 21-23 March 1977.

Johnson, W. Impact Strength of Materials. London: Edward Arnold, 1972.

Kolsky, H. Stress Waves in Solids. New York: Dover Publications Inc., 1963.

Kucher, V. "Multiple Impacts on Monolithic Steel." BRL-TR-02406, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1982.

Macaulay, M. Introduction to Impact Engineering. London: Chapman Hall, 1987.

Maenchen, G., and S. Sack. "The TENSOR Code," Methods in Computational Physics. Vol. 3, New York: Academic Press, 1964.

Malkus, D. S., and T. J. R. Hughes. "Mixed Finite Element Methods - Reduced and Selective Integration Techniques: A Unification of Concepts," Computational Methods in Applied Mechanical Engineering. Vol. 15, pp. 63-81, 1978.

Matuska, D. A., and J. J. Osborn. "HULL Documentation. Vol. I, Technical Discussion." Orlando Technology Inc., Shalimar, FL, 1986 (a).

Matuska, D. A., and J. J. Osborn. "HULL Documentation. Vol. II, HULL User's Guide." Orlando Technology Inc., Shalimar, FL, 1986 (b).

Matuska, D. A., and J. J. Osborn. "HULL Documentation. Vol. III, SAIL User's Guide." Orlando Technology Inc., Shalimar, FL, 1986 (c).

National Materials Advisory Board (NMAB). "Materials Response to Ultra-High Loading Rates." NMAB-356, National Materials Advisory Board, Washington, DC, 1980.

Noh, W. F. Report UCRL-52112, Lawrence Livermore Laboratory, Livermore, CA, 1976.

Rinehart, J. S. Stress Transients in Solids. HyperDynamics: Santa Fe, 1975.

Scheffler, D. R. "Two-Dimensional Computer Simulations of Segmented Penetrators." BRL-TR-3013, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1989.

Schultz, J. C. "Finite Element Hourglassing Control," International Journal of Numerical Methods in Engineering. Vol. 21, pp. 1039-1048, 1985.

Sedgwick, R. T., J. L. Waddell, and G. M. Wilkinson. "High Velocity Long Rod Impact: Theory and Experiment." Proceedings of the Tenth International Symposium on Ballistics, San Diego, October, 1987.

Silsby, G. F. "Penetration Mechanics of Anti-Armor Kinetic Energy Penetrators." LAB-R-GFS871 (available from G.F. Silsby, 303 Darlington Road, Havre de Grace, MD, 21078), 1987.

Sorensen, B. R., K. D. Kimsey, G. F. Silsby, D. R. Scheffler, T. M. Sherrick, and W. S. de Rosset. "High Velocity Penetration of Steel Targets," International Journal of Impact Engineering. To be published 1990.

Walsh, R. T. "Finite Difference Methods," Dynamic Response of Materials to Intense Impulsive Loading. Air Force Materials Laboratory, Wright-Patterson AFB, OH, 1973.

Walters, W. P., and J. A. Zukas. Fundamentals of Shaped Charges. New York: Wiley-Interscience, 1989.

Wilkins, M. L. "Use of Artificial Viscosity in Multidimensional Fluid Dynamic Calculations," Journal of Computational Physics. Vol. 36, pp. 281-303, 1980.

Wright, T. W. "Penetration With Long Rods: A Theoretical Framework and Comparison with Instrumented Impacts." BRL-TR- 02323, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1981.

Wright, T. W., and K. Frank. "Approaches to Penetration Problems," Impact: Effects of Fast Transient Loading. Rotterdam: A. A. Bakema, 1988.

Zukas, J. A., T. Nicholas, H. F. Swift, L. Greszczuk, and D. R. Curran. Impact Dynamics. New York: Wiley-Interscience, 1982.

Zukas, J. A. "Stress Waves and Fracture," Materials at High Strain Rates. London: Elsevier Applied Science Publishers, 1987.

Zukas, J. A. "Numerical Simulation of Semi-Infinite Target Penetration by Continuous and Segmented Rods." BRL-TR-3081, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1990.

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